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NEW APPROACHES TO CLEANING
OF LIQUID RADIOACTIVE WASTE

The industrial methods for disposal of liquid radioactive waste and cleaning of contaminated solutions containing heavy metals and radionuclides have been considered. If heavy metal ions are present only in ionic form, electrodialysis has been established to be the most effective cleaning method. If the components to be removed are present in ionic and colloidal forms, the preliminary destruction of colloidal and organic matter (by hydrodynamic cavitation, low-temperature plasma method, etc.) is necessary. The developed PTANK method enables an effective purification of multicomponent metal-containing solutions containing organic substances and complexes. The development of advanced membrane technologies and complex recycling schemes, as well as their synergistic combination will provide an opportunity to deeply clean the contaminated solutions and to minimize the secondary wastes.

K e y w o r d s : heavy metals, radionuclides, electrodialysis, hydrodynamic cavitation, and low-temperature plasma.

The nuclear power is one of the leading components of the power-generating industry. The world nuclear power is concentrated in approximately 30 countries where 439 nuclear reactors with a total capacity of 372.2 GW are located. Today, nuclear power plants (NPPs) generate over 15% of global electricity and a significant portion of national electricity in some countries. The existing nuclear power plants with their security systems are the most environmentally friendly and safe source of electricity as compared with other systems of power generation.

Ukraine has sufficient natural reserves in terms of raw material for generating nuclear power. There have been three uranium deposits on its territory. In addition, Ukraine is among the world leaders and the first among the CIS countries in terms zirconium reserves. It is ranked the third

world producer of zirconium concentrate (zircon) falling behind Australia and South Africa.

Given the present state of destroyed coal mining industry in the Donbas and the situation in the field of natural gas, the nuclear power is of particular relevance.

One of the negative consequences of the use of nuclear energy is radioactive waste (RW) [1], including a large amount of liquid radioactive waste (LRW) of low and medium activity the treatment of which is an integral part of radioactive waste management.

According to the environmental requirements and existing standards, the cost of LRW disposal per cubic meter increased sharply from USD 35, in 1965, to USD 140, in 1978, and further reached about USD 5800, in 1985. Nowadays, this upward trend persists. Therefore, reduction of radioactive waste is an urgent task, the solution of which effects the economic performance of nuclear power plants.

Currently, there are new technologies [2], advanced sorption materials, manufacturing equip-

ment [3], and control systems, which can significantly improve the existing scheme of LRW disposal and create conditions for the development of new equipment and processes. To remove radionuclides from solutions there are physicochemical methods based on *sorption, separation,* and *membrane* processes. The choice of method depends on the chemical and radionuclide composition of LRW and is defined by the state of radionuclides in solution [4, 5].

The sorption methods are based on the absorption and adhesion of radionuclides. In Ukraine, both organic and inorganic sorbents (for example, the modified chitin-based (*Mikoton*) and the lignin-based (*Foliox*) sorbents, as well as the sorbents based on natural finely dispersed layered silicates) are widely used [6]. The oxidation method based on the destruction of organic substances by ozone under various thermodynamic conditions and on the application of inorganic compounds emitting inorganic oxygen (potassium permanganate, chlorates, etc.) is used for the decomposition of complex compounds and destabilization of resistant forms of heavy metals [7, 8].

The membrane methods. The solution components are separated through ultrafiltration, reverse osmosis or electrodialysis due to ion transfer through semipermeable membrane [9–12]. These methods are promising for optimizing the LRW treatment at nuclear power plants because of low power consumption, high efficiency, and availability of advanced membranes.

Among *the thermal methods* of LRW treatment, the most noteworthy ones are distillation (evaporation) and drying. The distillation provides a high degree of purification from radionuclides condensate (10^5–10^6 Bq/l). The main disadvantages of these methods are high power consumption and the impossibility of cleaning liquids in which the radionuclides and heavy metals are present in colloidal or preudo-colloidal form insofar as the advanced membranes ensure the transport of substances only in the ionic form.

Today, there is an urgent need for new methods of disposal of multicomponent metal-containing radioactive waste, which organically combine the positive properties of both physical and chemical methods, and nanotechnology [13, 14]. The combination of several efficient LRW treatment processes using physical and chemical factors will significantly raise the environmental safety of industrial plants and facilities in the nuclear fuel cycle.

The averaged composition of contaminated waters (collected by special sewerage system) subject to processing by the evaporation method using the existing equipment of the chemical plant consists of waters entering the special sewerage system as a result of discharge of equipment, its washing and decontamination using regeneration solutions, as well as from showers and laundries [15].

These waters are polluted by mechanical impurities; *pH* is between 4 to 11 units; dry weight reaches 25 g/dm^3. The chemical composition is as follows: sodium ions (up to 1.5 g/dm^3), nitrate ions (up to 3.0 g/dm^3); chloride ions (up to 0.1 g/dm^3), iron ions (up to 0.007 g/dm^3); ammonium ions (up to 0.015 g/dm^3), sulfate ions (up to 0.6 g/dm^3), and petroleum products (up to 0.009 g/dm^3). The specific activity of water ranges from $1*10^4$ Bq/l to $1*10^6$ Bq/l; the major radionuclides are ^{137}Cs (up 92%), ^{90}Sr, ^{60}Co, and ^{134}Cs. The annual output of drain water ranges from 17 to 19 thousand m^3.

This complex multi-component and multiphase composition of contaminated water generated by nuclear power plants and uranium industry requires a special approach.

This research is aimed at reviewing and developing new approaches to cleaning of contaminated solutions that contain heavy metals and radionuclides, as well as at manufacturing plants for their implementation.

THE EXPERIMENTAL COMPONENT

If contaminated waters contain radionuclides in ionic form and a large quantity of soluble salts of alkali and alkaline earth metals, the membrane methods should be used [16, 17]. Among the membrane methods, the most cost effective and feasible is *electrodialysis.*
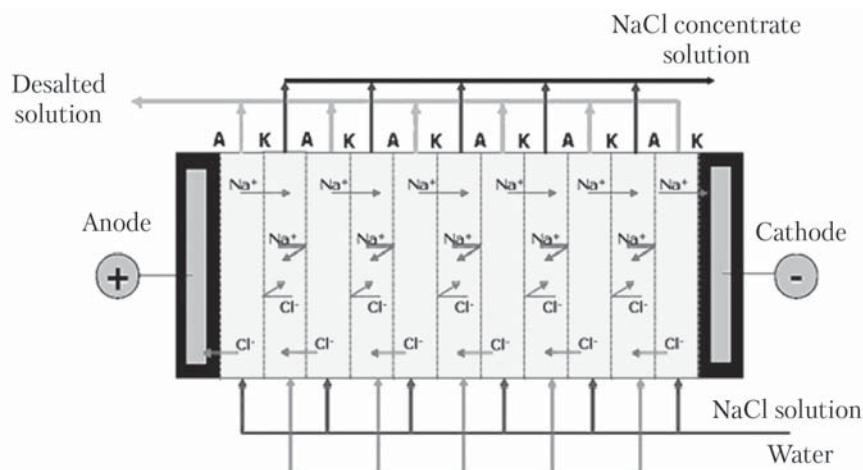
Fig. 1. Electrodialysis (membrane electrolysis): *A* — anion exchange membranes; *K* — cation-exchange membranes

To speed up the cleaning of dialyzed systems from electrolytes the dialysis in electric field (electrodialysis) is used. This method increases the cleaning rate ten times. Applying cation or anion exchange membranes with the help of electrodialysis it is possible to control the concentration of electrolyte solution. In multi-cell electrodialyzer, there is a large number (several hundreds) of alternating cation- and anion-exchange membranes located between two electrodes (Fig. 1). The electric current transfers cations from the initial solution to the flux of concentrate through the cation-exchange membrane located on the cathode side. The cations are detained by the anion-exchange membrane, on the cathode side. The anions move in the opposite direction. They are transferred to the flux of concentrate through the anion-exchange membrane.

Thus, the process is aimed at increasing the ion concentration in alternating cells, while reducing their concentration in the other cells.

The ion exchange membranes used for electrodialysis must have high electrical conductivity and high permeability to ions. In addition, they should have high selectivity, moderate swelling rate, and sufficient mechanical strength.

The electrodialysis is used most efficiently for the purification of waters in which the content of dissolved salts is approximately 10–20 g/l. In this case, electrodialysis is more cost effective as compared with reverse osmosis or evaporation [18, 19].

The technique of membrane electrolysis is promising for the separation and concentration of waters containing valuable components (for instance, uranium) before their removal. As compared with the reverse osmosis, the electrodialysis has an advantage of enabling the use of more thermally and chemically stable membranes, so the electrodialysis can be carried out at high temperature and at extremely low or high values of *pH*. Although, the use of electrodialysis for water purification is limited since it is impossible to remove the uncharged and colloidal components that may also be present.

The optimum conditions for removing ions from solutions by electrodialysis in terms of performance and power consumption are as follows: the salt content of source solution to be purified should be, at least, 4 g/l, the voltage should be less than 40V, and the feed rate should not exceed 100 l/h).
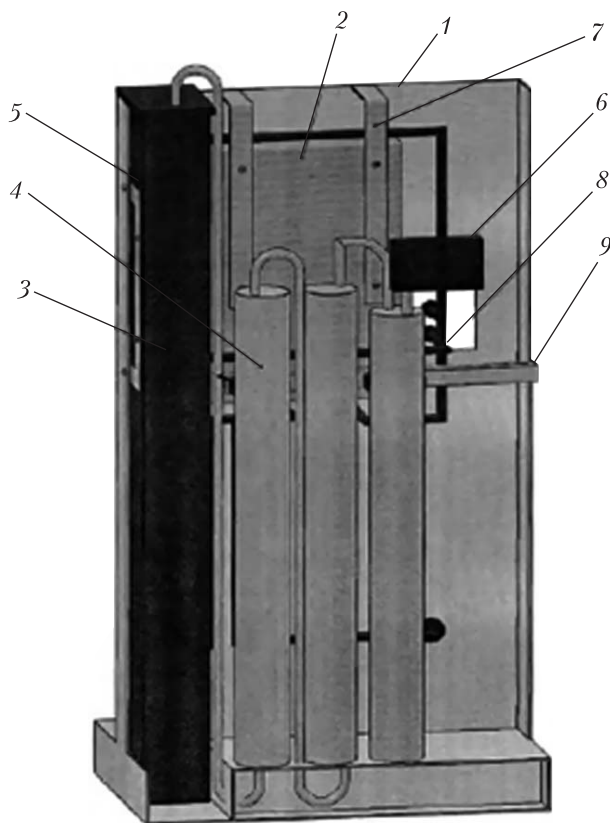
The author team has designed and developed an EDL-10 laboratory plant for removing the ions from solution. Its main part is the electrodialysis demountable module (Fig. 2). The electro-membrane unit is structured as a package consisting of se-
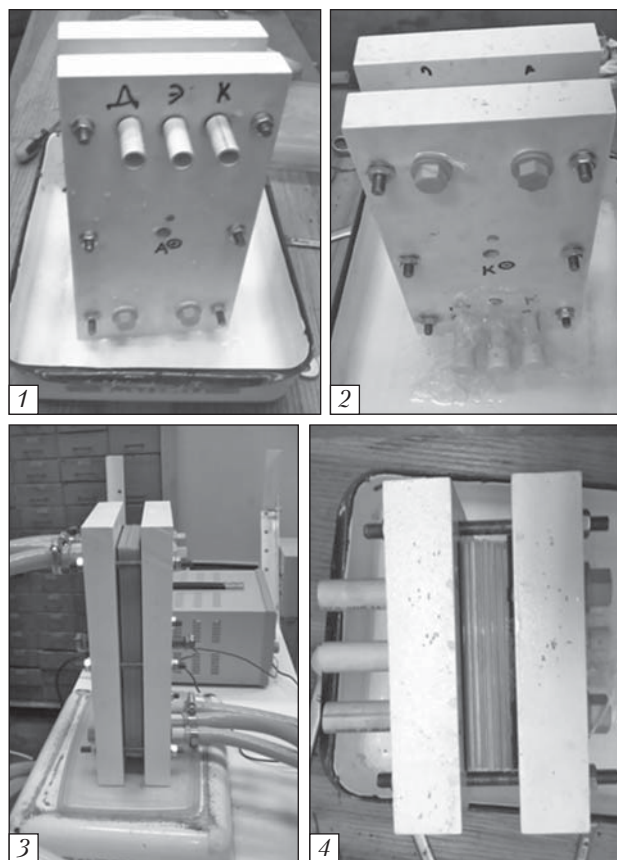
Fig. 2. General view of membrane module: *1* — tightening plates; *2* — inter-membrane labyrinth-type PE cushion with PE mesh (turbulators, ion membranes); electrodes imbedded in the tightening plates; *3* — 1/2 CPVC joint for connection to pipelines; *4* — stainless steel coupling pins with bolts and washers; rubber gaskets

Fig. 3. General view of the unit: *1* — frame; *2* — control unit; *3* — filter; *4* — dialyzer; *5* — heat exchanger; *6* — pressure monitor/flow meter; *7* — support of control unit; *8* — filter support; *9* — heat exchanger support

quential alternating ion exchange membranes and intermembrane gaskets placed between the clamping plates with integrated electrodes and pinned. During the operation, the solutions continuously flow through the respective cell system (Fig. 3). The outgoing flows from each track interfuse in prefabricated drainage channels. The end cells located directly at the electrodes are electrode cells.

For laboratory experiment on purification of low-active LRW by electrodialysis, a special working solution was prepared. It contained 4 g/l of salt, had a total hardness of 5.0 mg eq/l, *pH* of 11.7, and the following radiochemical composition: ^{137}Cs (880 Bq/l) and ^{90}Sr (10 Bq/l).

Before the test, the sample LRW solution passed through the rolled ultrafiltration element.

The flow chart of the laboratory electrodialysis plant is showed in Fig. 4.

During the test, the concentrated solutions and the sample solutions were pumped through the electrode cells. The salt content, dry residue, *pH*, hardness, and concentration and specific activity of Cs and Sr radionuclides were measured for the circulating solutions. Voltage on the electrodes and electric current in the cell were controlled throughout the process.

Electrolysis was carried out in the circulation mode, without adjustment of LRW *pH,* during 16 hours (8 hours daily, totally two days). The speed of circulation of the solution through all cells was

about 3 l/hour. The process was conducted at a constant voltage of 5.8 V that accounted for 70% of the voltage of critical current. The results are given in Table 1 and show that in the course of electrodialysis, the total salt content, hardness, and specific activity of radionuclides decrease. After 15 hours of electrodialysis, concentration of dissolved salts drops 16.5 times, total hardness downs 12.2 times, and the specific activity of Cs and Sr falls 10 and 12.6 times, respectively.

The results of LRW electrodialysis cleaning in the circulation mode with *pH* adjustment are given in Table 2 and show that after 23.5 hours, concentration of dissolved salts decreases 25.4 times, total hardness drops 20 times, and the specific activity of ^{137}Cs and ^{90}Sr falls 32.9 and 80.0 times, respectively.

Thus, the tests have showed that the electrodialysis method can be effectively used for the removal of soluble salts and ionic forms of radionuclides from the contaminated solutions contain-

Electrodialysis Purification of LRW in Circulating Mode without pH Adjustment

Time, hours	Solution	I, мА	*pH*	Salt content, g/l	Total hardness, mg-eq./l	Specific activity, Bq/l	
						^{137}Cs	^{90}Sr
0	LRW	180	11.7	3.3	5	890	240
1	Desalted medium	180	11.35	2.4	3.9	890	–
3	Desalted medium	170	11.3	1.9	2.6	622	95
5	Desalted medium	186	11.0	1.4	2.2	584	102
7	Desalted medium	150	10.7	1.1	1.7	355	76
9	Desalted medium	136	10.3	0.7	0.65	248	48
11	Desalted medium	69	9.95	0.5	0.6	135	29
13	Desalted medium	57	9.4	0.27	0.45	126	56
15	Desalted medium	40	9.1	0.2	0.41	89	19
15	Concentrate	140	12	9.4	0.17	7013	318

Electrodialysis Purification of LRW in Circulating Mode with pH Adjustment

| Time, hours	Solution	I, мА	*pH*	Salt content, g/l	Total hardness, mg-eq./l	Specific activity, Bq/l	
						^{137}Cs	^{90}Sr
0	LRW	290	11.7	3.3	5.0	560	240
3,0	Desalted medium	284	2.1	4.3	3.3	–	190
5,5	Desalted medium	222	3.3	1.55	3.1	330	134
7,5	Desalted medium	132	3.4	1.14	1.9	217	96
9,5	Desalted medium	133	3.4	0.88	1.5	131	66
11,5	Desalted medium	95	3.5	0.61	1.1	74	23
13,5	Desalted medium	74	3.0	0.67	0.75	56	31
15,5	Desalted medium	67	3.4	0.34	0.66	36	24
17,5	Desalted medium	51	3.5	0.27	0.50	29	6,4
19,5	Desalted medium	33	3.0	0.20	0.25	31	6,5
21,5	Desalted medium	28	3.65	0.13	0.30	34	12
23,5	Desalted medium	23	4.0	0.13	0.25	17	3
17,5	Concentrate	–	2.5	12.8	48	1910	596
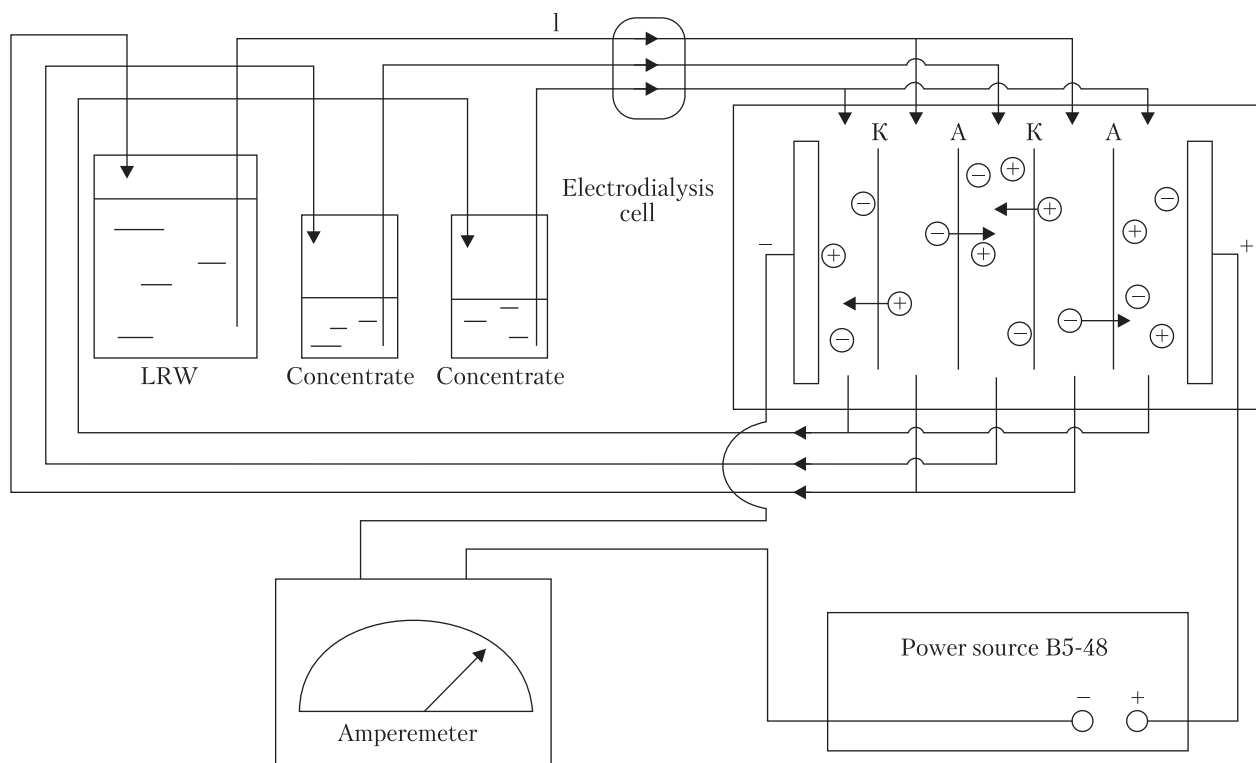
Fig. 4. Flow chart of laboratory unit for dialysis

ing heavy metals and radionuclides. The purification factor for cesium radionuclides is 30, while that for strontium radionuclides amounts to 80. The total desalination reaches 25 times.

Depending on specific conditions, LRW can be purified in the circulation or the flow modes, as well as in the partial recirculation mode.

LRW electrodialysis can be recommended in combination with microfiltration techniques and selective sorption of cesium, which enables excluding the ion exchange stage from the process. Another option of the use of electrodialysis is the partial desalination of LRW before the ion exchange to increase the filtering cycle of ion exchange columns.

The presence of surfactants that merge radionuclides while forming colloids leads to a significant decrease in the degree of purification. An important condition for using the membrane methods for LRW purification is preliminary destruction of organic matter present in the solution. As a result of the destruction of organic substances that are part of colloid and complex compounds, metal ions are released and can be removed by membrane methods.

Unlike the conventional methods of destruction of organic matter (oxidation with ozone, potassium permanganate, etc.) used for drain water purification, *the cavitation method* [20] can apply in this case. It provides for the formation of cavitation bubbles when aqueous solution passes through Laval nozzle.

Because under the influence of varying local pressure of fluid the bubbles can dramatically shrink and expand, the gas temperature inside the bubbles varies widely and can reach several hundred degrees Celsius. According to some estimates, the temperature inside the bubbles can reach 1500 °C. Also, it should be borne in mind that the gases dissolved in liquid contain more oxygen percentage as compared with the air, therefore the gases in bubbles are chemically more aggressive during the cavitation. This chemical aggressiveness of gases in bubbles combined with the influence of molecular oxygen causes
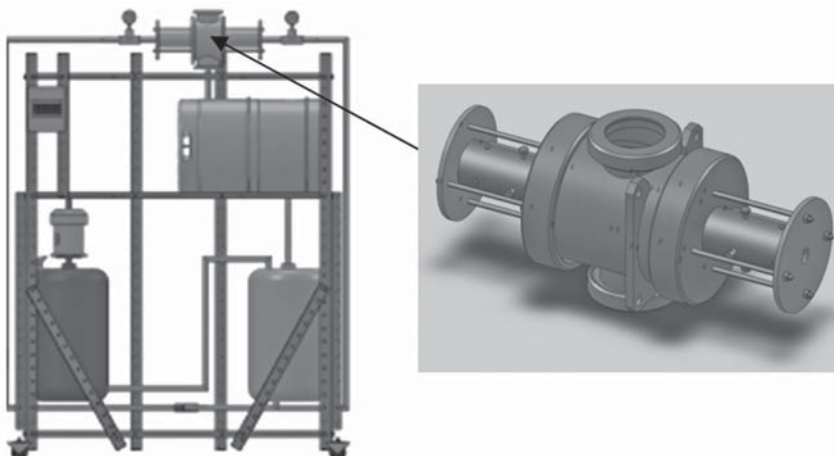
Fig. 5. Pilot hydrodynamic cavitation unit

destruction of materials facing "the cavitated" liquid [21]. As cavitation bubbles collapse, the energy of liquid is concentrated in very small volumes thereby creating areas with increased temperature.

For the experimental confirmation of practicability of the hydro-cavitation method for the destruction of organic compounds, including surfactants that are present in solution as crushed molecular particles, the author team has studied changes in NP-1 Sulfanol amount in aqueous solution.

To determine the Sulfanol content in aqueous solution, a standard method for measuring the mass concentration of surfactants in water (GOST R 51211-98 (introduced on 1999.07.01) Methods for Measuring the Content of Surfactants) has been used.

To study the effect of hydro-cavitation method on the solution of anionic surfactants (AS) a Sulfanol solution with a concentration of 100 mg/l was prepared. The experiment was carried out on a hydrodynamic cavitation unit (Fig. 5), in the Department for Nuclear Technologies at the Institute of Environmental Geochemistry of the NAS of Ukraine.

At regular intervals, 50 ml of treated solution was taken. The aqueous Sulfanol solution was activated in nine cycles. During the activation, the temperature of solution varied for the reasons described above. The results are presented in Table 3.

Having analyzed the data presented in Table 3, one can conclude that:
✦ Treatment of aqueous Sulfanol solution by hydro-cavitation leads to a partial destruction of Sulfanol molecules;
✦ Intensity of destruction depends on the conditions of experiment (number of cycles, flow rate of fluid, and operating mode of cavitator).

The most intense destruction of Sulfanol is reported at the initial stage of solution treatment. Further, the changes associated with recombination of fragments of Sulfanol molecules broken under the influence of cavitation bubbles are observed. During the recombination, new molecules of anionic surfactants whose structure has not been studied well are synthesized.

A more complete destruction of organic compounds, including surfactants, can be achieved by the *low-temperature plasma method* [22–24]. The destruction of organochlorine compounds in the low-temperature plasma chamber has been tested by example of hexachlorobenzene suspension, inasmuch as it is a very complex and poor-degradable substance. For this, laboratory complex AMC-1 was established (Fig. 6) in the mode of exclusive use of low-temperature plasma chamber, without any other devices and modes of physical impact on the suspension studied (magnetic separator, electrolysis, ultrasound). The power was supplied

from industrial three-phase network with a voltage of 220–380 V and a frequency of 50 Hz.

Current discharges having a voltage of 10 kV with a capacity of 30 kW/h and a frequency of discharge of 60 Hz passed through the plasma chamber consisting of four autonomous consecutive blocks. Working suspension was fed into the chamber using a pump having a capacity of 1200 l/h.

Plant Operation Mode:

Voltage of electric pulse: We = 10 kV in the reaction chamber of each channel;

Numbers of channels engaged: 4;

Frequency of generated pulses of each channel: f = 10 Hz;

Capacity: 0.33 l/s or 1900 l/hour;

Quantity of energy generated: 300 kJ/l.

For obtaining the hexachlorobenzene (HCB) suspension, hexachlorobenzene crystals were dissolved in a small amount of dimethylketone (acetone) for 24 hours at a temperature of 50–60 °C. The resulting solution was brought into the reaction vessel containing 30 liters of water (for reaching a C_6Cl_6 concentration of 3.3 mg/l), by small portions, with constant mixing.

Before turning the AMC-1 on, a 0.5 liter control sample of HCB suspension was taken. The resulting solution was treated in the circulation mode for 1 min, 3 min, and 7 min.

The destruction was carried out in three stages.

At first stage, HCB suspension passed through the low-temperature plasma chamber. After this, the product was placed in a separate container and the second test sample was taken.

At the second stage, the suspension (approximately 29 liters) cyclically passed through the working chamber and collector. The AMC-1 continuous operation lasted 3 minutes. Then, the unit was stopped, and the third 0.5 liter test sample was taken.

The third stage was a repeat of the second stage with the fourth sample taken.

To determine the concentration of HCB in the original suspension and in the treated suspension the method of *thin-layer chromatography* was used. To make analysis, special chromatographic plates coated with a thin layer of adsorbent (aluminum oxide) applied. The test material was applied to the start line, with a special sample deposited near. The plate was placed in eluating solution in thin-layer chromatographer. After the end of the experiment, the plate was taken out and dried at an ambient temperature to remove the solvent completely. To identify chromatographic spots a special lamp with hard ultraviolet radiation was used. The amount of C_6Cl_6 was estimated based on the luminescence intensity.

Studies have showed that the concentration of HCB in the initial suspension was 3.33 mg/l; after the treatment, it decreases more than 6 times (0.5 mg/l). After the first treatment, the concen-

Table 3

Effect of Hydrocavitation on Sulfanol Solution

Parameter	Initial value	1	2	3	4	5	6	7	8	9
t, °C	22.9	22.9	28.3	29.7	30.7	32.7	32.8	38.8	41.4	42.4
		29.3	31.9	32.3	32.9	32.8	38.9	41.4	44.6	53.4
ΔQ. kJ		161	90	65	55	3	6	65	80	276
E	0.850	0.537	0.599	0.759	0.528	0.565	0.729	0.547	0.484	0.725
ΔE		+313	−62	−160	+231	−37	−164	+182	+63	−241
$\Delta E/\Delta Q$		+1.94	−0.69	−2.46	+4.20	−12.3	−27.3	+2.80	+0.79	−0.87

Note. I = 12 V; *U* = 390 V; *t* is temperature of solution, °C; *Q* is change in the amount of heat obtained from hydro-cavitation, kJ; *E* is optical density of chloroform extract, which is related with AS content in the solution by expression $S = k * E$, where *C* is concentration of surfactant, *g; k* is conversion factor that depends on surfactant concentration and thickness of cuvette.
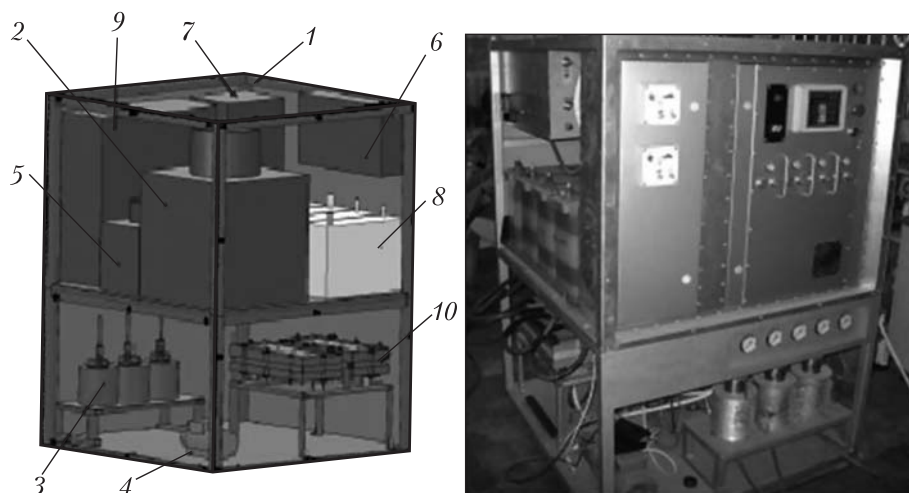
Fig. 6. AMC laboratory complex: *1* — frame; *2* — reactor; *3* — centrifuge; *4* — pump; *5* — ignition block; *6* — control unit; *7* — control unit; *8* — spark gap; *9* — container; *10* — power converter

tration of HCB decreases down to 0.75 mg/l, after the second, it drops to 0.62 mg/l, and after the third, it falls down to 0.51 mg/l.

The effect of low-temperature plasma generated by AMC-1 on the tested HCB suspension is a sharp decline (more than 6 times) in the content of toxic organochlorine substances in the working fluid. The analysis of the samples has showed a tenfold drop in HCB concentration after the first cycle, with the indicators reaching an ambient level and increasing during the process.

If destruction of organic matter is practically inappropriate, the contaminated fluids that contain both heavy metals and radionuclides in ion-

ic and colloidal form are cleaned by the PTANK method [25, 26]. The proposed method involves a sequence of the following processes. In the solution to be purified a nano-sized sorbent (colloidal dispersion) having a negative electro-kinetic potential is synthesized. The sorbent absorbs the pollutants not only by its condensed part, but also by its surface and is synthesized directly in the bulk of solution (the first colloidal system). The absorption of pollutants by the sorbent condensed part prevents a reverse diffusion of absorbed substances from the sorbent into the environment. A hetero-coagulation process is proposed to use for depositing the obtained colloidal system. For this,

Table 4

Absorption of LRW Pollutants by Silica Magnetite Composite

Initial concentration of pollutants, mg/l								pH	Initial concentration of pollutants, mg/l				
Cs	Sr	Co	Cu	Fe^{+2} / Fe^{+3}	Sulfanol	$Na_2B_4O_7$	SF—2		Cs	Sr	Co	Cu	Fe^{+2}/ Fe^{+3}
26	20	14	12	15 000	–	–	–	6–7	65	92	82	94	97
10	6	4	5	13 000	–	–	–	7–8	67	96	97	90	99
10	6	4	5	13 000	–	–	500	7–8	62	94	99	88	99
63	62	42	45	5000	–	–	–	9	73	97	94	95	99
63	62	42	45	5000	–	2000	–	9	72	96	93	97	99
63	62	42	45	5000	500	–	–	9	75	97	93	97	99
63	62	42	45	5000	500	2000	–	9	73	98	92	95	98

the second colloid system containing positively charged nanoparticles is synthesized in the same solution. The presence of oppositely charged systems and radionuclides in pseudo-colloid form provides a sufficiently high completeness of cleaning. As a result of hetero-coagulation, a coagulant containing components of the first and the second colloidal systems is formed. It incorporates pollutants absorbed from the solution. After the completion of hetero-coagulation, a nanocomposite (coagulant) is obtained by separation of the solid and liquid phases by sedimentation method with filtration. To intensify the separation of coagulant and supernatant fluid it is advisable to apply direct electric current and centrifugation method.

Thus, the proposed method for cleaning the fluids contaminated with heavy metals and radionuclides (in the presence of surfactants) includes a synthesis of colloidal nanoparticles of poly-silicon acids in the solution with further precipitation by sol of nano-magnetite obtained in the same solution under the influence of pulsed magnetic field [27].

The analysis of filtrate obtained as a result of separation of the solid and liquid phases has showed that almost all cations present in the solution transit from the dispersion medium to the nanocomposite (Table 4).

One can see from the above data that for 1 cycle, 7% Cs, 97% Sr, 93% Co, 97% Cu, and 99% Fe^{+2}/Fe^{+3} transit from the dispersion medium to the nanocomposite. The presence of dispersion medium surfactants (Sulfanol, SF-2) in an amount of 0.5 g/l has virtually no negative impact on the removal of these cations. The iron introduced into the system as Fe^{+2}/Fe^{+3} salts is almost completely deposited on the silica colloid.

CONCLUSIONS

1. It has been established that the method of electrodialysis can be effectively used to clean the aqueous solutions containing heavy metals, hardness salts, and radionuclides in ionic forms. The EDL-10 plant has been designed. It operates in the circulation mode and is equipped with a detachable electro-dialysis module. Purification

ratio for cesium is 30, while that for strontium is 80. The total desalination reaches 25. Among the disadvantages of this method, there is a sharp decrease in the efficiency of cleaning of contaminated liquids in the presence of surfactants.

2. For the destruction of surfactants present in contaminated liquids, an experimental hydrodynamic cavitation unit has been designed in the Department for Nuclear Technologies. Laboratory studies using the above unit have showed that the treatment of Sulfanol aqueous solution by the hydro-cavitation method leads to a partial destruction of Sulfanol molecules. The intensity of destruction of organic matter depends on the experiment conditions (number of cycles, flow rate of fluid, operating mode of cavitator).

3. For a more complete destruction of organic compounds present in contaminated fluids, including hexachlorobenzene, a laboratory complex AMC-1 has been designed and established in the mode of exclusive use of low-temperature plasma chamber, without any other devices and modes of physical impact on the suspension studied (magnetic separator, electrolysis, ultrasound). The studies have showed that the low-temperature plasma generated by AMC-1 has an effect on the tested HCB suspension as it causes a sharp decline (more than 6 times) in the content of toxic organochlorine substances in the working fluid.

4. To clean the contaminated fluids containing both heavy metals and radionuclides in colloidal and ionic pseudo-colloid form in the presence of organic matter, in one cycle, a special method of purification has been developed. The proposed method is called PTANK and implemented under the influence of pulsed magnetic field. The research has showed that for 1 cycle, 7% Cs, 97% Sr, 93% Co, 97% Cu, and 99% Fe^{+2}/Fe^{+3} transit from the dispersion medium to the nanocomposite. The presence of dispersion medium surfactants (Sulfanol, SF-2) in an amount of 0.5 g/l has virtually no negative impact on the removal of these cations.

5. Using the above methods separately, in some cases, it is impossible to clean the contaminated liquids having a complex chemical and radionu-

clide composition. This problem can be solved by developing advanced membrane technologies and integrated treatment schemes. The synergistic combination thereof will enable deep cleaning of contaminated fluids containing both heavy metals and radionuclides and minimization of secondary waste.

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НОВІ ПІДХОДИ ДО ОЧИЩЕННЯ
РІДКИХ РАДІОАКТИВНИХ ВІДХОДІВ

Розглядаються індустріальні методи очищення рідких радіоактивних відходів та техногенно забруднених розчинів, що містять важкі метали та радіонукліди. По-

казано, що у випадку, коли іони важких металів знаходяться виключно у іонній формі, найбільшу ефективність очищення має метод електродіалізу. Розроблено метод ТОНАК, який дозволяє ефективно очищувати багатокомпонентні металовмісні техногенні розчини, які містять серед іншого органічні речовини та комплексоутворювачі. Розробка сучасних мембранних технологій, створення комплексних схем переробки та їх синергічне поєднання дасть можливість досягти глибокого очищення техногенно забруднених розчинів, а також мінімізувати об'єм вторинних відходів

Ключевые слова: важкі метали, радіонукліди, електродіаліз, гідродинамічна кавітація, низькотемпературна плазма.

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НОВЫЕ ПОДХОДЫ К ОЧИСТКЕ
ЖИДКИХ РАДИОАКТИВНЫХ ОТХОДОВ

Рассматриваются индустриальные методы очистки жидких радиоактивных отходов и техногенно загрязненных растворов, содержащих тяжелые металлы и радионуклиды. Показано, что в случае, когда ионы тяжелых металлов находятся исключительно в ионной форме, наибольшую эффективность очистки имеет метод электродиализа. Разработано метод ТОНАК, который позволяет эффективно очищать многокомпонентные металлосодержащие техногенные растворы, содержащие среди прочего органические вещества и комплексообразователи. Разработка современных мембранных технологий, создание комплексных схем переработки и их синергическое сочетание позволит достичь глубокого очищения техногенно загрязненных растворов, а также минимизировать объем вторичных отходов.

Ключевые слова: тяжелые металлы, радионуклиды, электродиализ, гидродинамическая кавитация, низкотемпературная плазма.